

**Title:** Friction stir weld restart+reweld repair allowables**Summary:**

A friction stir weld (FSW) repair method that yields mechanical properties comparable to initial welds has been developed and implemented on Al 2195 plate material used in fabrication of the Space Shuttle External Fuel Tank (ET). The method includes restarting the weld, in instances where an initial weld prematurely terminated followed by two reweld passes. Room temperature and cryogenic temperature mechanical properties exceeded initial weld design strength. A-basis repair allowables were slightly lower than initial weld A-basis allowables. Simulated service test data confirmed that no change to the critical flaw size or inspection requirements was necessary. In addition, the mechanical properties of Variable Polarity Plasma Arc (VPPA) fusion weld intersections at the friction stir repair weld was shown to be similar to initial VPPA fusion to friction stir weld intersections. Porosity (up to 0.7 inch) at the toe of the fusion weld did not adversely affect the intersection strength. No stress gradients due to the presence of a restart and multiple rewelds were demonstrated by photo stress analysis in the FSW repair.

**Abstract:**

A friction stir weld (FSW) repair method has been developed and successfully implemented on Al 2195 plate material for the Space Shuttle External Fuel Tank (ET). The method includes restarting the friction stir weld in the termination hole of the original weld followed by two reweld passes. Room temperature and cryogenic temperature mechanical properties exceeded minimum FSW design strength and compared well with the development data. Simulated service test results also compared closely to historical data for initial FSW, confirming no change to the critical flaw size or inspection requirements for the repaired weld. Testing of VPPA fusion/FSW intersection weld specimens exhibited acceptable strength and exceeded the minimum design value. Porosity, when present at the intersection was on the root side toe of the fusion weld, the "worst case" being 0.7 inch long. While such porosity may be removed by sanding, this "worst case" porosity condition was tested "as is" and demonstrated that porosity did not negatively affect the strength of the intersection weld. Large, 15-inch "wide panels" FSW repair welds were tested to demonstrate strength and evaluate residual stresses using photo stress analysis. All results exceeded design minimums, and photo stress analysis showed no significant stress gradients due to the presence of the restart and multi-pass FSW repair weld.

**Introduction**

Friction stir welding (FSW) is performed on longitudinal barrel welds of the Space Shuttle External Fuel Tank (ET). The majority of these welds are Al2195 to Al2195 welds, although a few are bimetallic Al2219 to Al2195. When an unscheduled weld termination occurs, a hole is left in the weld where the pin tool stopped. Development testing shows that the ideal repair methodology is to restart the FSW in the termination

hole and complete the weld, followed by two subsequent reweld passes. This methodology successfully consumes the termination hole, gives mechanical properties similar to initial welds, and has been implemented for multiple termination holes as well. Development data showed that two reweld passes yielded more consistent mechanical properties and better consolidation of the restart location.

When the first FSW termination occurred on an ET weld, the restart plus two pass reweld (R+R) method was selected for repairing the weld. However, a termination in the first reweld pass occurred due to a tooling problem. Because of this, the restart plus two pass reweld method was chosen to repair the termination in the first reweld pass for the initial weld (yielding a total of four weld passes).

## Procedure

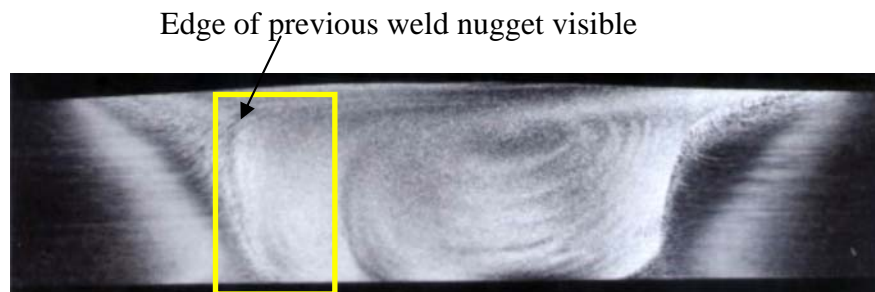
Testing was done to confirm the R+R methodology for weldability, strength, fracture and to assure the integrity of subsequent fusion intersection welds. Standard preweld cleaning was performed on each panel, including draw filing and scraping near the start and stop ends, followed by isopropyl alcohol wipe and wire brush of the remainder of the weld joint. Tack welding and the FSW penetration pass were made in conformance with the process requirements, except for the planned terminations and restarts. All restart welds were made with a retractable pin tool and completed in accordance with the repair weld schedule.

FSW panels were submitted for inspection following completion of all welding. The crown and root sides were prepared for Non-Destructive Evaluation (NDE), including penetrant inspection, radiography, and phased array ultrasonics. Following NDE, panels were sectioned and machined to produce tensile, simulated service and wide panel specimens, as well as pieces for welding into fusion weld to FSW intersections.

## Discussion of Results

### *Macro examination*

Macros were taken from R+R panels and analyzed. A representative macro is shown in Figure 1. The presence of multiple weld passes is clearly seen. No rejectable indications were seen in macros.



**Figure 1. Three pass reweld macro (3X magnification).**

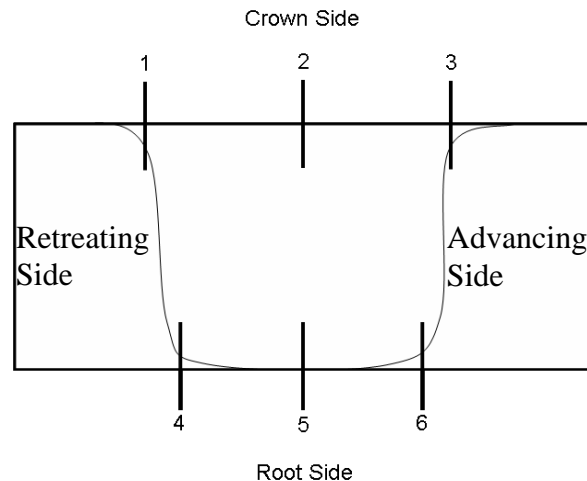
### *Tensile testing*

Tensile specimens were tested in accordance with ASTM E8 at either room temperature or -423°F (cryogenic tests per ASTM E1450). A-basis allowables at room temperature and -423°F were calculated. At room temperature there was no difference between initial weld and repaired weld A-basis allowables, but there was an approximately 5 ksi drop in repair allowables at -423°F compared to initial weld strength.

### *Simulated Service Tests*

Simulated service test (SST) specimens were used to test the multi-pass FSW (2 pass and 3 pass) as well the as restart locations (restart in an initial FSW and restart in reweld). The weld restart location, if present, was centered in the width of the specimen. A 0.15 inch deep (a) X 0.75 inch long (2c) pre-crack flaw was used for SST. Pre-crack flaws were tested in six locations in the weld repairs as shown in Figure 2.

SST begins with a room temperature proof test to imminent failure followed by post proof radiography and penetrant inspections prior to simulated service cycles which represent 4 missions (lifetimes). Upon completion of cyclic testing each specimen was tested to fracture to measure residual strength.



**Figure 2. Pre-crack flaw locations.**

The SST results for this testing were in family with development test results of initial FSW for 0.75 inch long pre-crack flaws. No significant difference was observed between the residual strength of a 2 pass reweld versus a 3 pass reweld.

### *Wide Panels*

Four wide panels were welded and tested for strength and to evaluate residual stresses. Wide panel specimens were ~40 inch long by ~20 inch wide welded panels machined to a dog-bone configuration, yielding 15 inch gage width for testing.

Each wide panel contained an initial weld and two restart welds spaced evenly within the 15 inch initial gage width. A 3 pass FSW reweld was performed on each wide panel. No pre-crack flaws were induced in these panels.

Each wide panel was proof tested to 30 ksi at room temperature followed by post proof radiographic and penetrant inspections prior to testing to fracture.

All wide panels met the minimum design strength requirements. All panels were radiographically acceptable with indications less than 0.065 inches (if present). Photo stress analysis was performed on one wide panel while being tested to fracture. No stress concentrations at the restart locations or in the rewelds were seen. This confirms that there were no significant visible stress concentrations in the wide panel due to the restarts or rewelds.

#### *Fusion to FSW Intersections*

External tank FSWs are intersected at the start and stop ends by Variable Polarity Plasma Arc (VPPA) fusion welds. Seventeen fusion-to-FSW R+R intersections were welded and tested. Nine intersections received scraping between FSW passes, while eight did not. Automated VPPA intersecting welds were made in the vertical position using Al4043 filler wire, perpendicular to the FSW to simulate circumferential fusion weld intersections. Testing of intersection welds included a room temperature proof test to 30 ksi followed by post proof radiography and penetrant inspection, prior to testing to fracture.

All intersection specimens exceeded the design strength requirements for initial weld intersections. All intersections fractured on the 2219 side of the specimen opposite the FSW except for one specimen containing 0.60 inch porosity. Six of the seventeen intersections were radiographically acceptable to the tightest intersection criteria for intersection welds (up to 0.080 inch indication), while the other eleven exhibited porosity in magnitude up to 0.70 inch. Porosity, when present, was partially involved in the fractures of the three worst-case intersections (0.60 inch to 0.70 inch).

There was no significant difference between 2 pass and 3 pass rewelds with regard to the overall properties at the VPPA/FSW intersection. Scraping and brushing prior to reweld passes tended to produce fewer and smaller radiographic porosity indications at the intersection weld, which agrees with previous development data.

#### **Conclusion**

In conclusion, multiple tensile and fracture tests, as well as wide panel tests were performed in order to characterize the a Friction Stir Weld Restart Repair (FSW R+R). FSW repair weld tensile strength allowables have been estimated at approximately 5 ksi lower than initial weld strength. All fracture test data was in family with legacy FSW fracture testing. Photo stress analysis showed that the restart and reweld locations do not

affect the stress distributions in the weld. Fusion/FSW repair weld intersection strength was comparable to fusion/FSW intersection data from initial FSW tests. Scraping and brushing prior to reweld passes tended to produce fewer and smaller porosity indications at the intersection weld.

# **Friction Stir Weld Restart+Reweld Repair Allowables**

**Andrew Clifton  
Materials Engineer  
Lockheed Martin  
Michoud Operations  
504-257-3547  
[Andrew.C.Clifton@lmco.com](mailto:Andrew.C.Clifton@lmco.com)**



# Outline

- **Introduction**
- **Procedure**
- **Results**
- **Conclusions**



# Introduction

- **Space Shuttle External Fuel Tank (ET) is manufactured by Lockheed Martin in New Orleans**
- **Conventional friction stir welding (FSW) used on longitudinal barrel welds**
- **Most welds are Al2195 to Al2195; some are bimetallic Al2219 to Al2195**

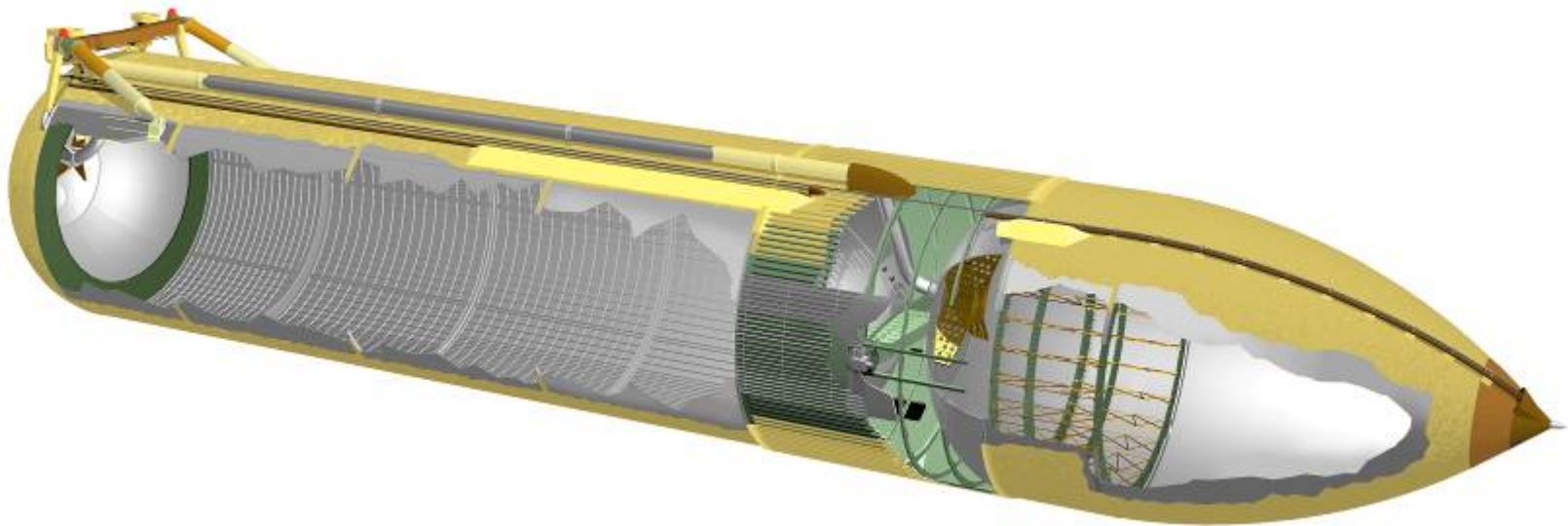




# Introduction



- **Cutaway view of External Tank:**



# Introduction



- **Unscheduled weld termination causes a hole where the pin tool stopped**
- **Development testing led to a standard repair methodology:**
  - **Restart the FSW in the termination hole**
  - **Complete initial weld**
  - **Complete two reweld passes through initial weld**



**Termination hole left by friction stir weld**

# Introduction



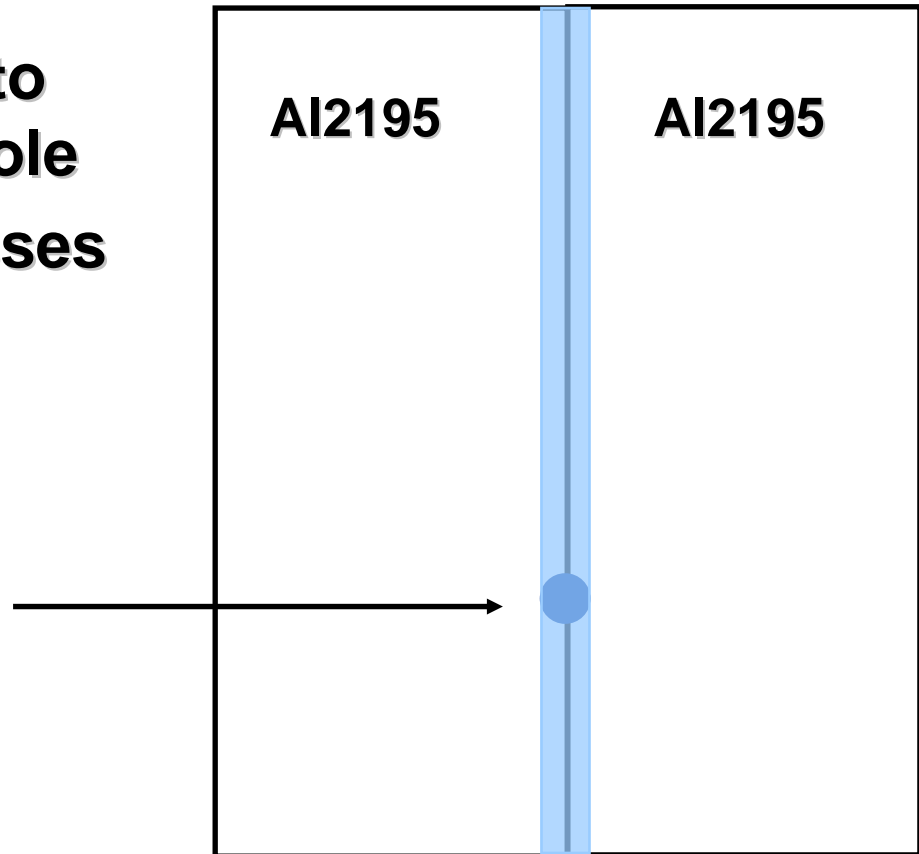
- **First FSW termination on an ET weld occurred in 2007**
- **Standard restart+reweld (R+R) repair methodology selected**
- **During first reweld pass, another problem caused a second termination**
- **Termination in reweld led to the question: what is the best way to repair the repair weld?**
- **Decided that the best way to repair the repair weld would be with the standard reweld methodology**

# Standard R+R Methodology



- Weld restarted in termination hole
- Two reweld passes to repair termination hole
- Three total weld passes

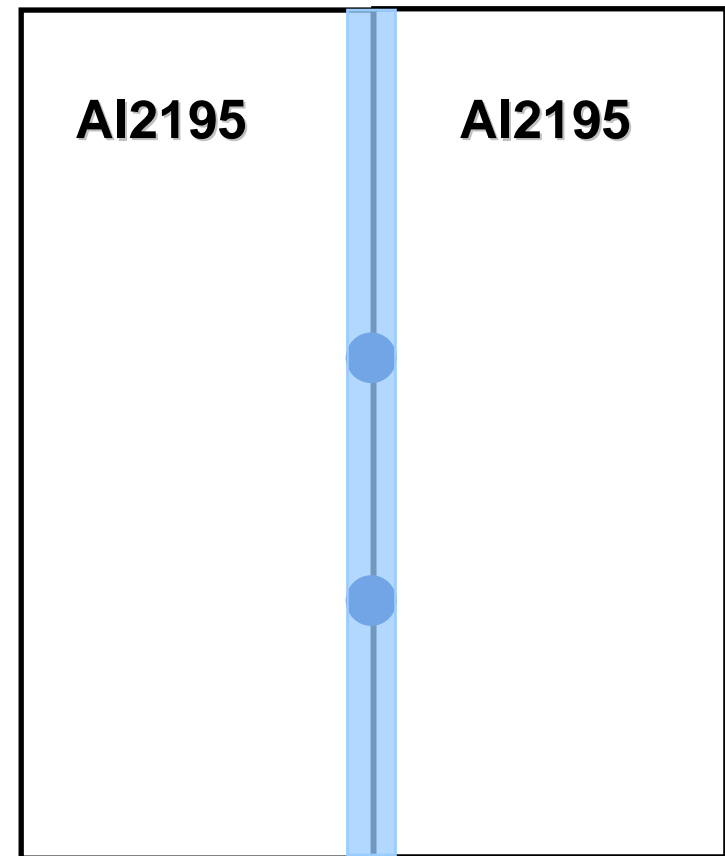
Termination hole  
in initial weld



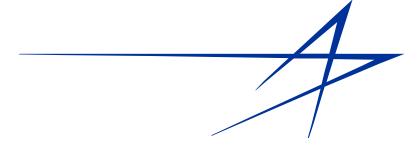
# Repaired R+R Methodology



- **Weld restarted in termination hole**
- **Termination in first reweld**
- **Restart the first reweld**
- **Two additional reweld passes**
- **3 full-length reweld passes**
- **Four total weld passes**



# Procedure



- **Test plan initialized to confirm restart plus reweld (R+R) methodology – Standard R+R as well as Repaired R+R**
  - **Macros (16)**
  - **Tensile tests – room temperature and -423°F (74)**
  - **Simulated service tests (30)**
  - **Wide panels (4)**
  - **Fusion to FSW intersections (17)**
  - **16 panels total (between 20-240 inches long)**

# Results – Macro Examination



- One macro from each panel – 16 total
- No rejectable indications in macros (typical below)



**No metallographic defects due to R+R repairs**

# Results – Tensile Testing



- **Tested the following conditions:**
  - **Standard R+R**
  - **Standard R+R, initial termination location**
  - **Repaired R+R**
  - **Repaired R+R, initial termination location**
  - **Repaired R+R, second termination location**
- **1 inch gage for regular tensile specimens; 3 inch gage for termination locations**
- **Tests at room temperature or -423°F**
- **Total of 74 tensile specimens**



# Results – Tensile Testing



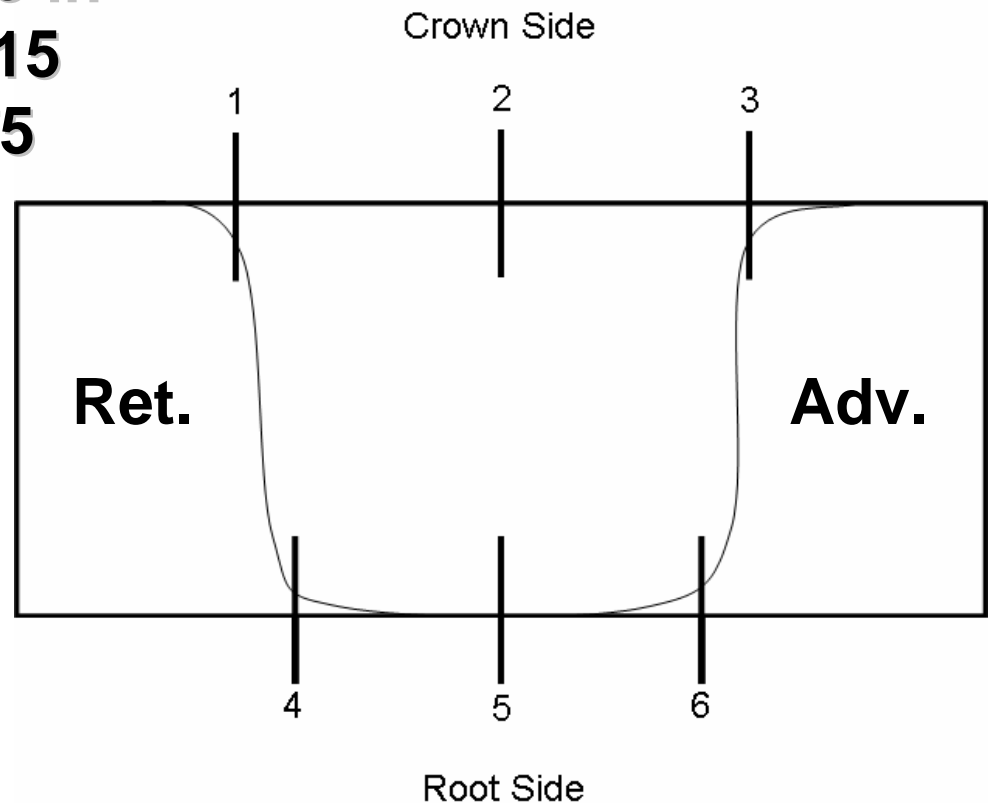
- **A-basis calculated for repaired welds:**
  - No reduction in room temperature UTS
  - 5 ksi lower than initial weld at at -423°F
- **Representative fracture face showing restart location:**



# Simulated Service Tests (SSTs)



- Three inch gage width specimens
- Pre-crack flaw made in each specimen – 0.15 inch deep (a) by 0.75 inch long (2c)
- Flaw at one of six locations:



# Simulated Service Tests (SSTs)



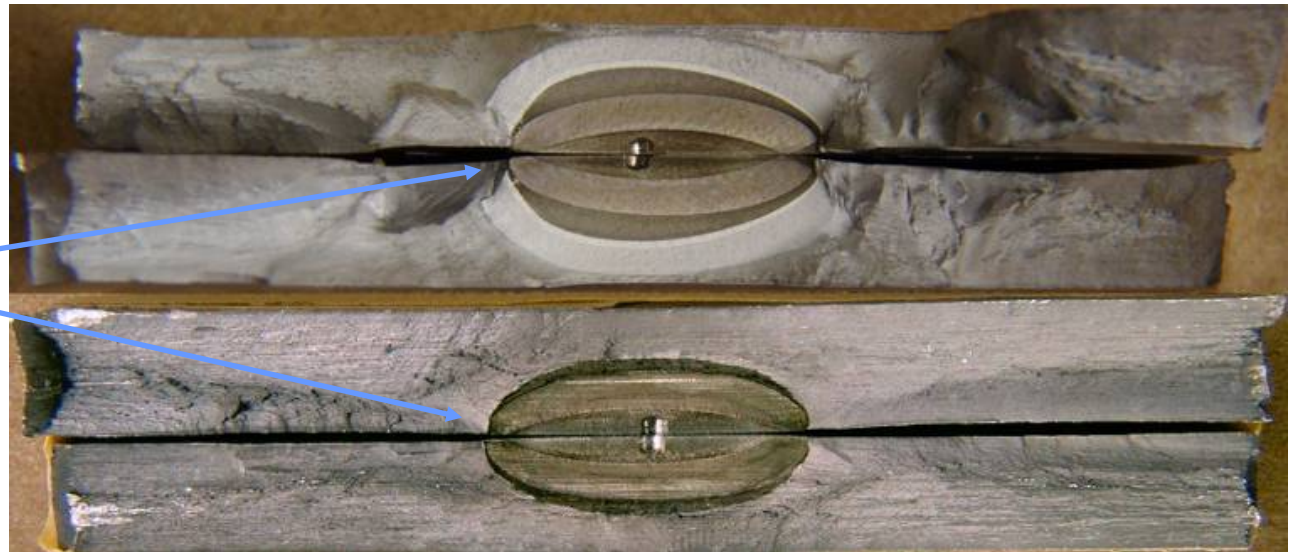
- **Testing begins with proof test to imminent failure**
- **Radiographic and penetrant inspections performed to measure crack growth**
- **Specimens subjected to cyclic stresses representing 4 missions (lifetimes)**
- **After 4 missions, specimens pulled to fracture to measure residual strength**

# Simulated Service Tests (SSTs)

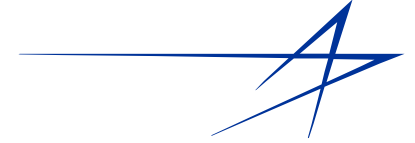


- **Thirty specimens tested**
- **Standard R+R and Repaired R+R tested, including termination locations**
- **SSTs performed at room temperature and -423°F**

**pre-cracks**



# Simulated Service Tests (SSTs)



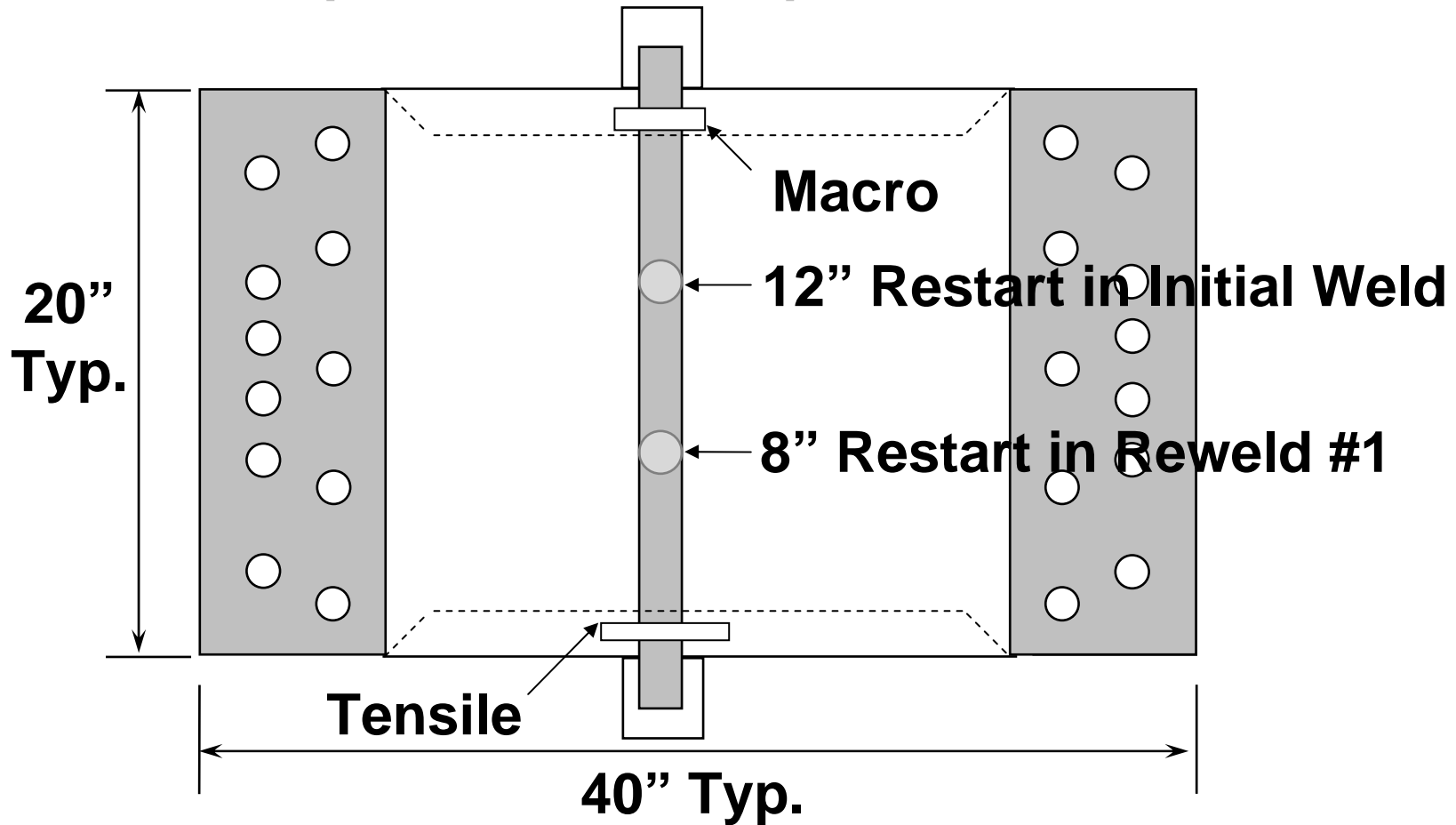
- **Results in family with development data for initial FSW**
- **No significant difference between Standard R+R and Repaired R+R**

**No change in fracture properties for R+R welds**

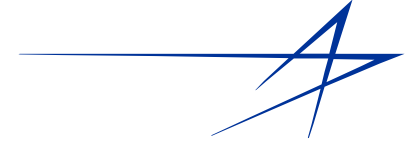
# Wide Panels



- Four Repaired R+R wide panels:



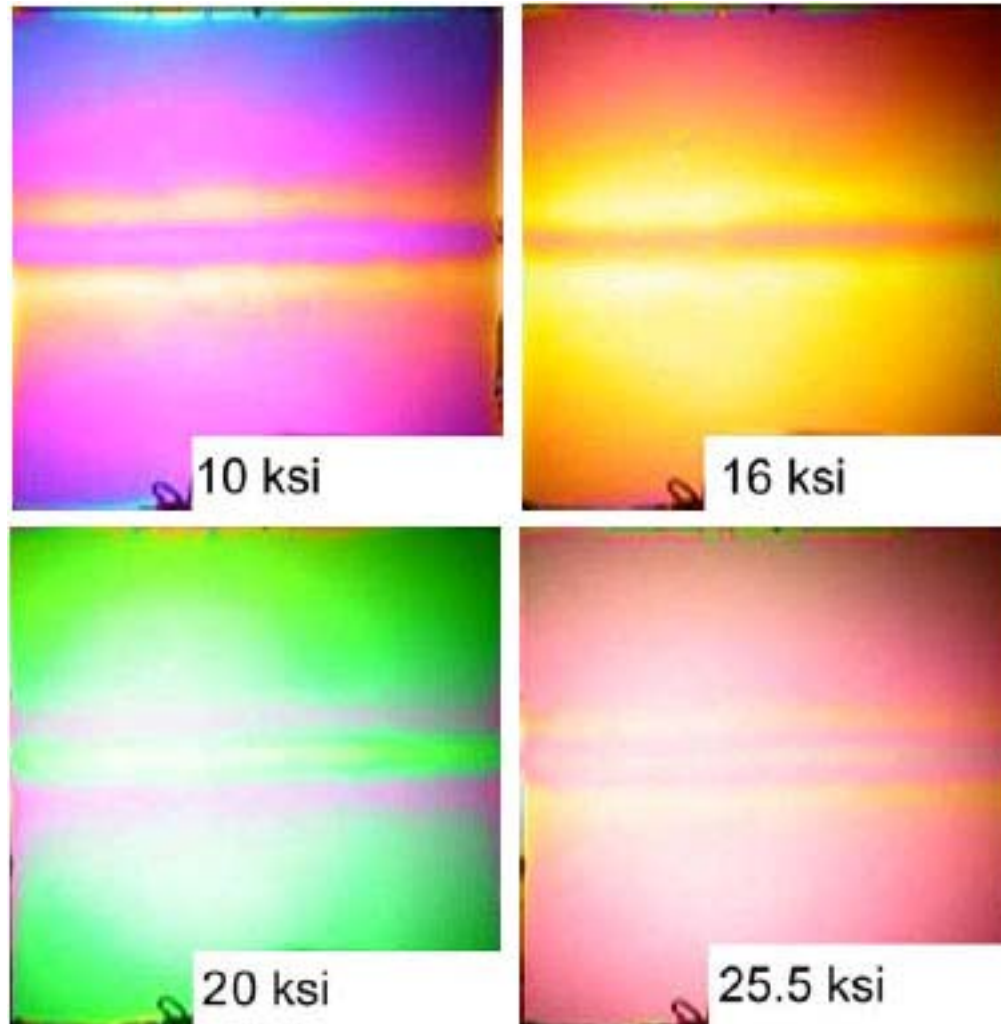
# Wide Panels



- **Each panel proof tested to 30 ksi, followed by radiographic and penetrant inspections**
- **Tested to fracture to measure strength**
- **All panels radiographically acceptable to tightest criteria (indications less than 0.065 inch)**
- **All panels met minimum design values for initial welds**
- **Photostress analysis showed no stress concentrations**

**No change in tensile values of wide panels**

# Wide Panels – Photostress





# Fusion to FSW Intersections

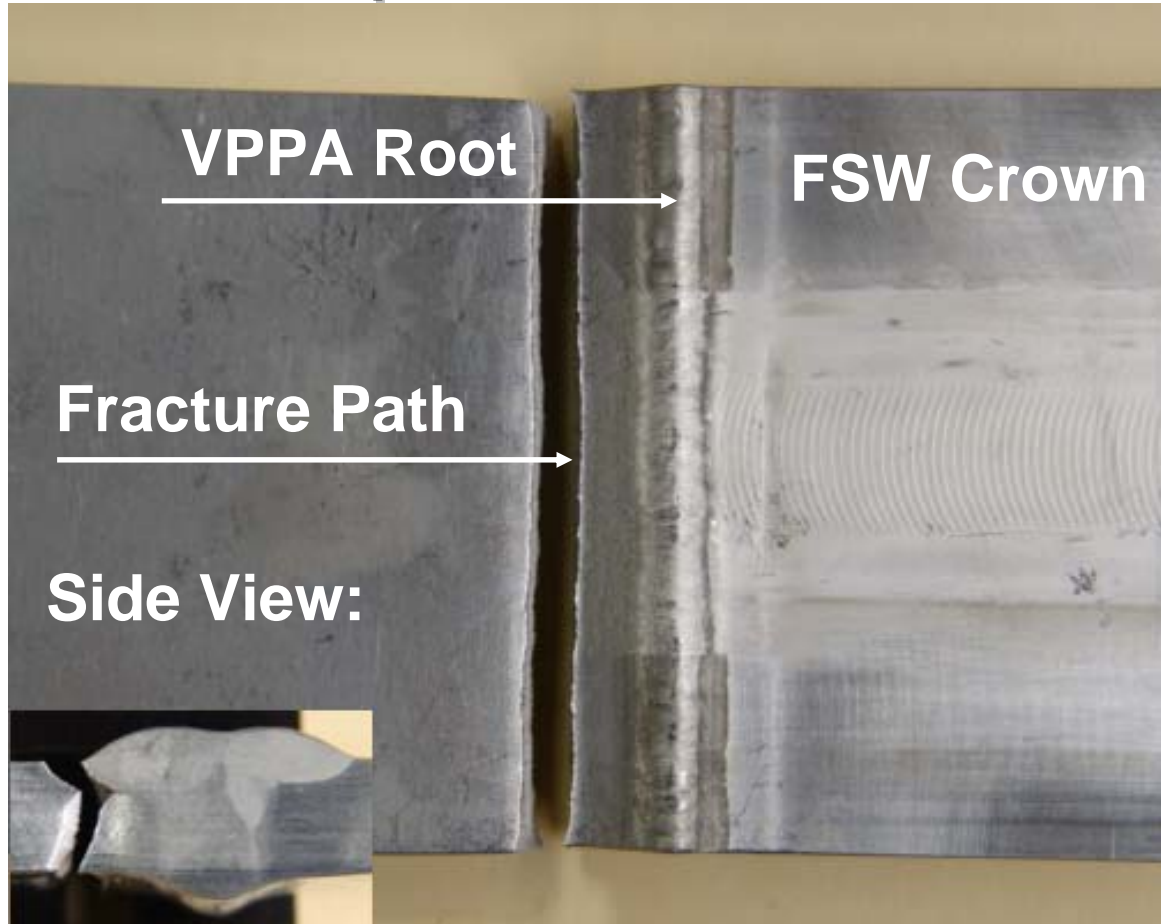


- **ET FSWs are intersected at the start and stop end by Variable Polarity Plasma Arc (VPPA) fusion welds**
- **Seventeen specimens welded**
  - **Nine received scraping between FSW passes, eight did not**
- **Automated VPPA using Al4043 filler wire**
- **Test sequence:**
  - **Room temperature proof test to 30 ksi**
  - **Radiographic and penetrant inspection**
  - **Test to fracture at room temperature or -423°F**

# Fusion to FSW Intersections



- **Typical fracture path:**

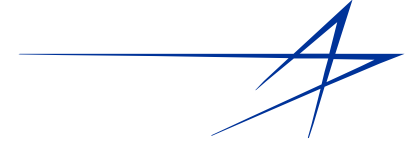


# Fusion to FSW Intersections



- **All intersections exceeded design strength requirements**
- **All specimens fractured on 2219 side of specimen opposite FSW except for one specimen containing 0.6 inch porosity at fusion root toe**
- **Porosity up to 0.7 inch tested “as is” and did not adversely affect strength**

# Fusion to FSW Intersections



- **Scraping and brushing between passes produced fewer and smaller radiographic porosity indications**
- **No difference noted between Standard R+R and Repaired R+R intersections**

**No adverse effect on fusion to FSW intersections due to repair**

# Conclusions



- **Macros**
  - No metallographic indications or defects observed
- **Tensile tests**
  - A-basis allowables calculated for R+R welds
  - No reduction in UTS at room temperature
  - ~5 ksi reduction in UTS at -423°F
- **Simulated service tests**
  - Results in family with initial weld properties

# Conclusions



- **Wide panels**
  - **Tensile properties exceed initial weld design values**
  - **No stress distributions due to repair**
- **Fusion to FSW Intersections**
  - **Properties exceed initial weld intersection design values**

**Standard R+R and Repaired R+R are acceptable repair methods**

